R Graphics Lectures

Computer Graphics

- Drawing graphics in a window on the screen of a computer is very similar to drawing by hand on a sheet of paper.
- We begin a drawing by getting out a clean piece of paper and then deciding what scale to use in the drawing.
- With those basic decisions made, we can then start putting pen to paper.
- The steps in R are very similar.

Starting a New Plot

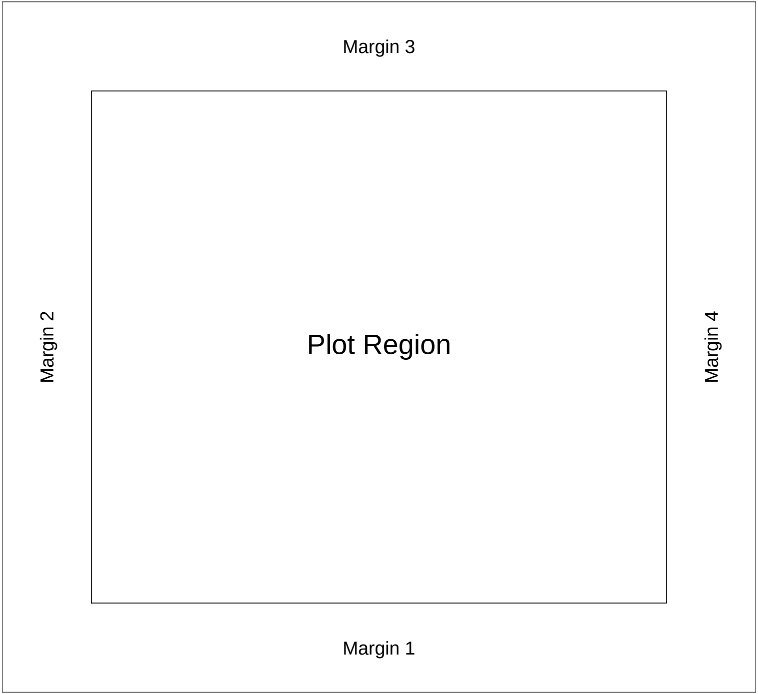
We begin a plot by first telling the graphics system that we are about to start a new plot.

```
> plot.new()
```

This indicates that we are about to start a new plot and must happen before any graphics takes place.

The call to `plot.new` chooses a default rectangular *plotting region* for the plot to appear in.

The plotting region is surrounded by four *margins*.


Margin 3
Margin 2
Plot Region
Margin 4
Margin 1

Controlling The Margins

The sizes of the margins can be changed by making a call to the function `par` before calling `plot.new`.

Set the margin sizes in inches.

```
> par(mai=c(2, 2, 1, 1))
```

Set the margin sizes in lines of text.

```
> par(mar=c(4, 4, 2, 2))
```

Set the plot width and height in inches.

```
> par(pin=c(5, 4))
```

Setting the Axis Scales

Next we set the scales on along the sides of the plot. This determines how coordinates get mapped onto the page.

```
> plot.window(xlim = xlimits, ylim = ylimits)
```

The graphics system arranges for the specified region to appear on the page.

`xlimits` and `ylimits` are vectors which contain lower and upper limits which are to appear on the x and y axes.

For example,

```
... xlim = c(-pi, pi), ylim = c(-1, 1), ...
```

might be suitable for plotting sine and cosine functions.

Manipulating the Axis Limits

The statement

```
> plot.window(xlim = c(0, 1), ylim = c(10, 20))
```

produces axis limits which are expanded by 6% over those actually specified. This expansion can be inhibited by specifying `xaxs="i"` and/or `yaxs="i"`.

For example, the call

```
> plot.window(xlim = c(0, 1), ylim = c(10, 20),
              xaxs = "i")
```

produces a plot with 0 lying at the extreme left of the plot region and 1 lying at the extreme right.

Aspect Ratio Control

There is also an optional argument to the function `plot.window()` which allows a user to specify a particular aspect ratio.

```
> plot.window(xlim = xlimits,
              ylim = ylimits,
              asp = 1)
```

The use of `asp=1` means that unit steps in the x and y directions produce equal distances in the x and y directions on the page.

This is important if circles are to appear as circles rather than ellipses.

Drawing Axes

The `axis` function can be used to draw axes at any of the four sides of a plot.

```
axis(side)
```

The value of the `side` arguments which axis is drawn.

`side=1` :	below the graph (x axis),
`side=2` :	to the left of the graph (y axis),
`side=3` :	above the graph (x axis),
`side=4` :	to the right of the graph (y axis).

A variety of optional arguments can be used to control the appearance of the axis.

Axis Customisation

The axis command can be customised. For example:

```
axis(1, at = 1:4, labels = c("A","B","C","D"))
```

places the tick marks on the lower x axis at 1, 2, 3, and 4 and labels them with the strings “A”, “B”, “C” and “D”.

Label rotation can be controlled with the value of the optional `las` argument.

- `las=0` : labels are parallel to the axis,
- `las=1` : labels are horizontally oriented,
- `las=2` : labels are at right-angles to the axis,
- `las=3` : labels are vertically oriented.

Additional Axis Customisation

Additional customisation can be produced with additional arguments to the `axis` function:

`col` :	the colour of the axis and tickmarks,
`col.axis` :	the colour of the axis labels,
`font.axis` :	the font to be used for the axis labels.

Colours can be specified by name (e.g. `"red"`, `"green"`, etc) as well as in other ways (see later).

Fonts can be one of `1`, `2`, `3` or `4` for *normal*, *bold*, *italic* and *bold-italic*.

Plot Annotation

The function `title` can be used to place labels in the margins of a plot.

```
title(main=str, sub=str, xlab=str, ylab=str)
```

The arguments are as follows:

- `main` : a main title to appear above the graph,
- `sub` : a subtitle to appear below the graph,
- `xlab` : a label for the x axis,
- `ylab` : a label for the y axis.

Customising Plot Annotation

The elements of the plot annotation can be customised with additional optional arguments.

`font.main`, `col.main`, `cex.main`
: The font (1, 2, 3, or 4), colour and magnification-factor for the main title.

`font.sub`, `col.sub`, `cex.sub`
: The font, colour and magnification-factor for the subtitle.

`font.lab`, `col.lab`, `cex.lab`
: The font, colour and magnification-factor for the axis labels.

Framing a Plot

It can be useful to draw a box around a plot. This can be done with the function `box`. The call

```
> box()
```

draws a box around the plot region (the region within the plot margins). The call

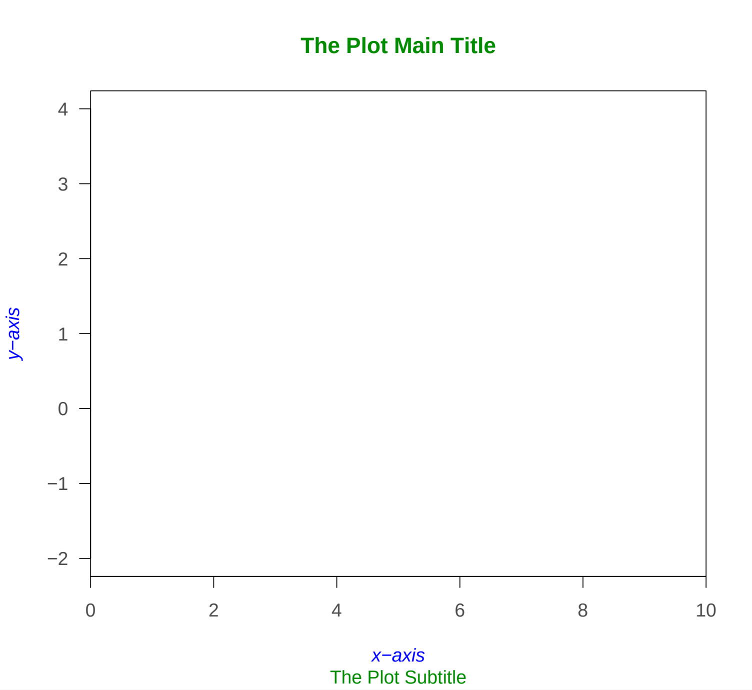
```
> box("figure")
```

draws a box around the figure region (the region containing the plot and its margins).

An optional `col` argument makes it possible to specify the colour for the box.

Example: A “Bare” Plot

```
> plot.new()
> plot.window(xlim = c(0, 10),
              ylim = c(-2, 4), xaxs = "i")
> box()
> axis(1, col.axis = "grey30")
> axis(2, col.axis = "grey30",
       las = 1)
> title(main = "The Plot Main Title",
        col.main = "green4",
        sub = "The Plot Subtitle",
        col.sub = "green4",
        xlab = "x-axis", ylab = "y-axis",
        col.lab = "blue", font.lab = 3)
> box("figure", col = "grey90")
```


The Plot Main Title
4
3
2
1
0
−1
−2
y−axis
0
2
4
6
8
10
x−axis
The Plot Subtitle

Some Drawing Primitives

- Points
- Connected Line Segments
- Straight Lines Across A Plot
- Disconnected Line Segments
- Arrows
- Rectangles
- Polygons
- Text
- Legends

Drawing Points

The basic call has the form:

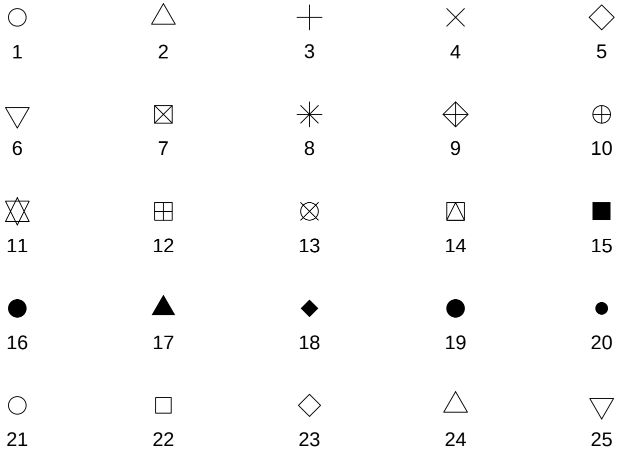
```
points(x, y, pch=int, col=str)
```

where:

- `pch` specifies the plotting symbol. Values 1 to 25 are special graphical symbols, values from 33 to 126 are taken to ASCII codes. A quoted character will also work,
- `col` gives a colour specification. Examples are, `"red"`, `"lightblue"`, etc. (More on colour later.)

Graphical Plotting Symbols

The following plotting symbols are available in R.

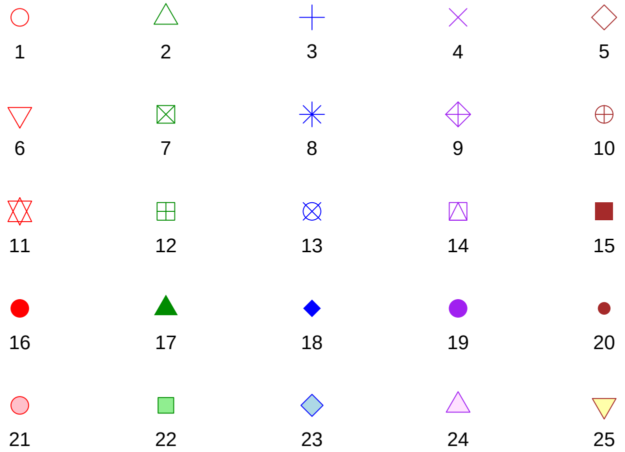


Plotting Symbols and Colour

- The colour of plotting symbols can be changed by using the `col` argument to `points`.
- Plotting symbols 21 through 25 can additionally have their interiors filled by using the `bg` argument to `points`.

Coloured Plotting Symbols

The effect of colour choice on plotting symbols.



Drawing Connected Line Segments

The basic call has the form:

```
lines(x, y, lty=str, lwd=num, col=str)
```

where:

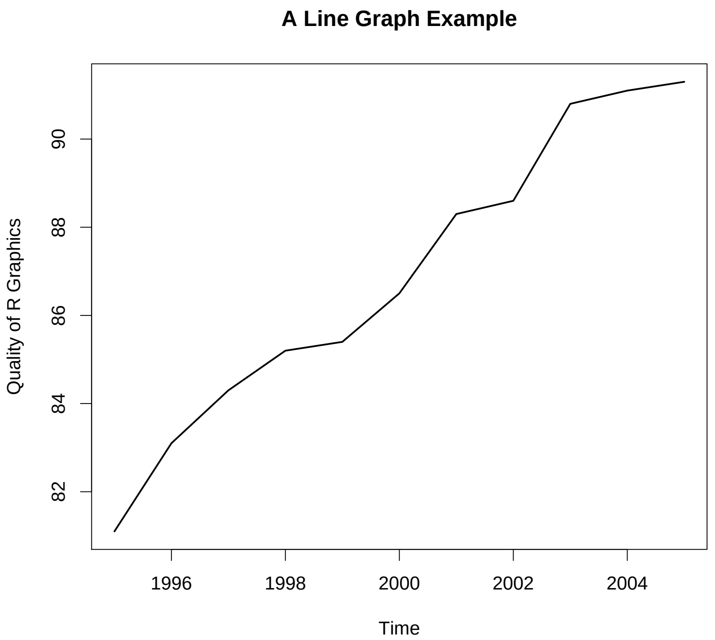
- `lty` specifies the line texture. It should be one of `"blank"`, `"solid"`, `"dashed"`, `"dotted"`, `"dotdash"`, `"longdash"` or `"twodash"`.

  Alternatively the length of on/off pen stokes in the texture. `"11"` is a high density dotted line, `"33"` is a short dashed line and `"1333"` is a dot-dashed line.

- `lwd` and `col` specify the line width and colour.

A Line Graph

```
> x = 1995:2005
> y = c(81.1, 83.1, 84.3, 85.2, 85.4, 86.5,
        88.3, 88.6, 90.8, 91.1, 91.3)
> plot.new()
> plot.window(xlim = range(x),
              ylim = range(y))
> lines(x, y, lwd = 2)
> title(main = "A Line Graph Example",
        xlab = "Time",
        ylab = "Quality of R Graphics")
> axis(1)
> axis(2)
> box()
```


A Line Graph Example
Quality of R Graphics
82
84
86
88
90
1996
1998
2000
2002
2004
Time

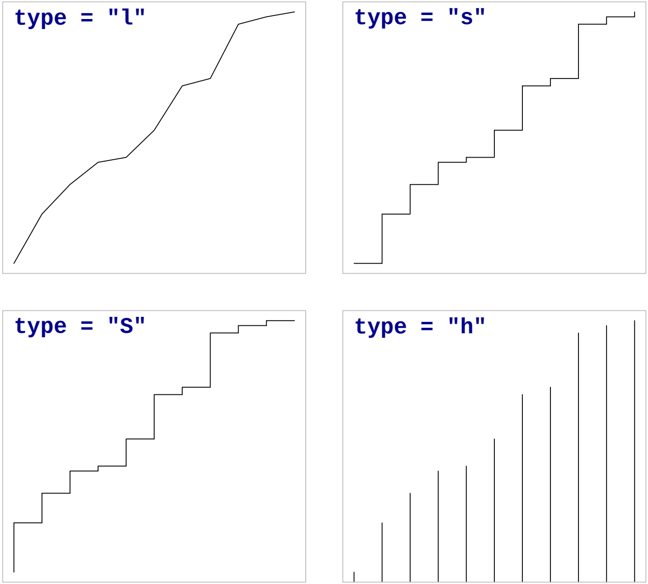
Line Graph Variations

Additional forms can be produced by the `lines` function. This is controlled by the `type` argument.

- `type="l"` : line graph,
- `type="s"` : step function — horizontal first,
- `type="S"` : step function — vertical first,
- `side="h"` : high density (needle) plot.

Additional variations:

- `type="p"` : draw points,
- `type="b"` : both points and lines,
- `type="o"` : over-plotting of points and lines,


type = "l"
type = "s"
type = "S"
type = "h"

Drawing Straight Lines

The basic call has the forms:

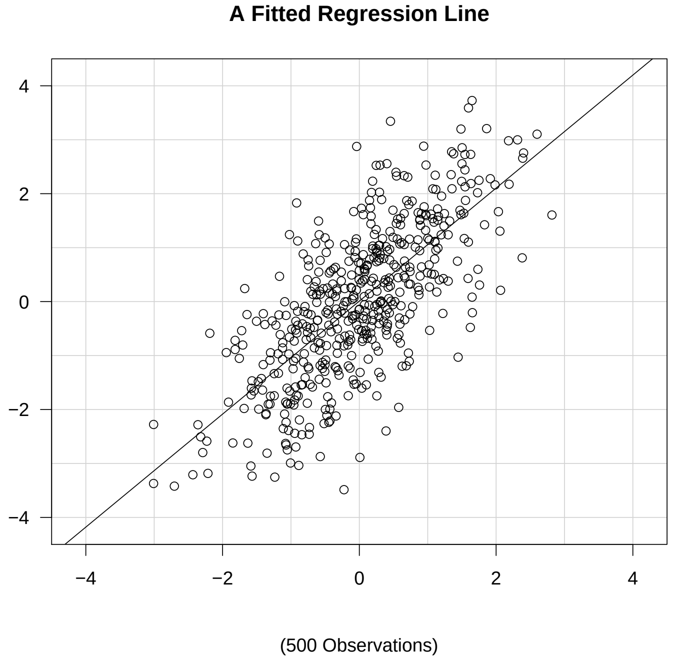
```
abline(a=intercept, b=slope)
abline(h=numbers)
abline(v=numbers)
```

where

- The `a` / `b` form specifies a line in intercept / slope form.
- `h` specifies horizontal lines at the given y values.
- `v` specifies vertical lines at the given x values.
- Line texture, colour and width arguments can also be given.

Straight Line Example

```
> x = rnorm(500)
> y = x + rnorm(500)
> plot.new()
> plot.window(xlim = c(-4.5, 4.5), xaxs = "i",
              ylim = c(-4.5, 4.5), yaxs = "i")
> z = lm(y ~ x)
> abline(h = -4:4, v = -4:4, col = "lightgrey")
> abline(a = coef(z)[1], b = coef(z)[2])
> points(x, y)
> axis(1)
> axis(2, las = 1)
> box()
> title(main = "A Fitted Regression Line")
> title(sub = "(500 Observations)")
```


A Fitted Regression Line
4
2
0
−2
−4
−4
−2
0
2
4
(500 Observations)

Drawing Disconnected Line Segments

The basic call has the form:

```
segments(x0, y0, x1, y1)
```

where

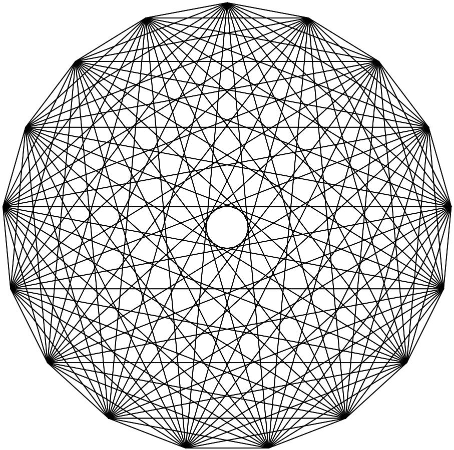
- The `x0`, `y0`, `x1`, `y1` arguments give the start and end coordinates of the segments.
- Line texture, colour and width arguments can also be given.

Rosettes

A rosette is a figure which is created by taking a series of equally spaced points around the circumference of a circle and joining each of these points to all the other points.

```
> n = 17
> theta = seq(0, 2 * pi, length = n + 1)[1:n]
> x = sin(theta)
> y = cos(theta)
> v1 = rep(1:n, n)
> v2 = rep(1:n, rep(n, n))
> plot.new()
> plot.window(xlim = c(-1, 1),
              ylim = c(-1, 1), asp = 1)
> segments(x[v1], y[v1], x[v2], y[v2])
```

A Rosette with 17 Vertexes

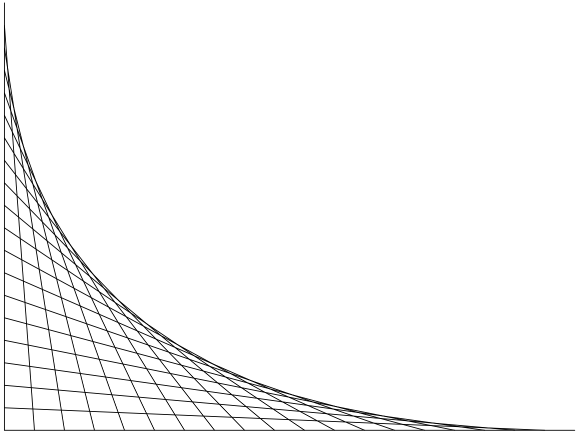


A Curve Envelope

Here is another example which shows how the eye can perceive a sequence of straight lines as a curve.

```
> x1 = seq(0, 1, length = 20)
> y1 = rep(0, 20)
> x2 = rep(0, 20)
> y2 = seq(0.75, 0, length = 20)
> plot.new()
> plot.window(xlim = c(0, 1),
              ylim = c(0, 0.75), asp = 1)
> segments(x1, y1, x2, y2)
> box(col = "grey")
```

A Curve Envelope



Drawing Arrows

The basic call has the form:

```
arrows(x0, y0, x1, y1, code=int,
       length=num, angle=num)
```

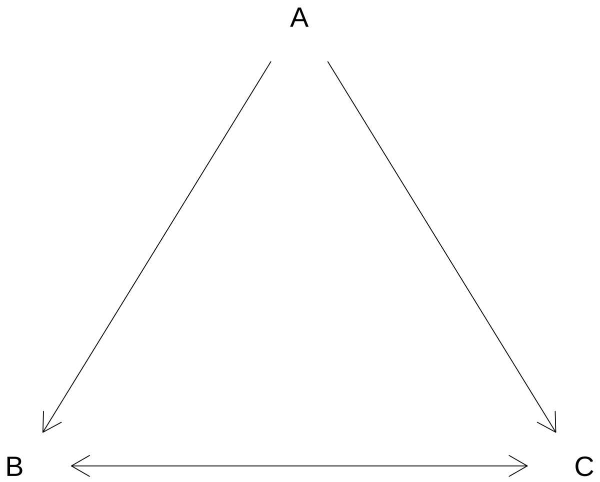
where

- The `x0`, `y0`, `x1`, `y1` arguments give the start and end coordinates of the arrows.
- `code=1` – head at the start, `code=2` – head at the end and `code=3` – a head at both ends.
- `length` and `angle` – length of the arrow head and angle to the shaft.

Basic Arrows

Here is a simple diagram using arrows.

```
> plot.new()
> plot.window(xlim = c(0, 1), ylim = c(0, 1))
> arrows(.05, .075, .45, .9, code = 1)
> arrows(.55, .9, .95, .075, code = 2)
> arrows(.1, 0, .9, 0, code = 3)
> text(.5, 1, "A", cex = 1.5)
> text(0, 0, "B", cex = 1.5)
> text(1, 0, "C", cex = 1.5)
```

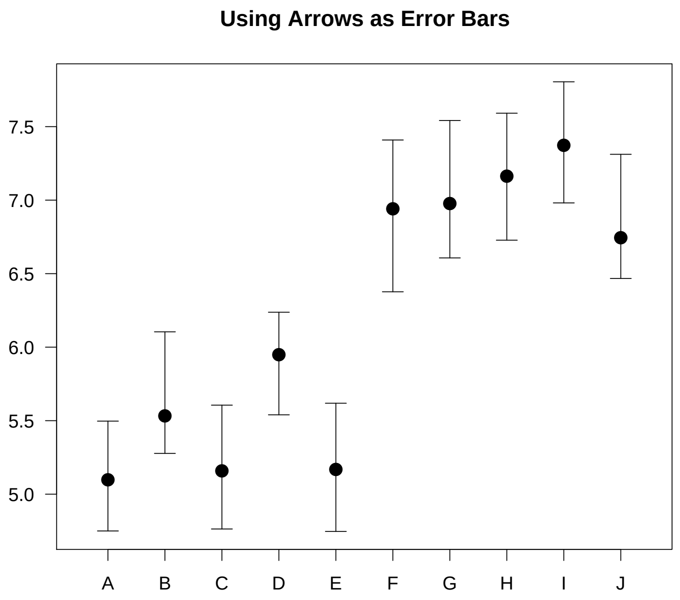

A
B
C

Using Arrows as Error Bars

```
> x = 1:10
> y = runif(10) + rep(c(5, 6.5), c(5, 5))
> yl = y - 0.25 - runif(10)/3
> yu = y + 0.25 + runif(10)/3
> plot.new()
> plot.window(xlim = c(0.5, 10.5),
              ylim = range(yl, yu))

> arrows(x, yl, x, yu, code = 3,
         angle = 90, length = .125)
> points(x, y, pch = 19, cex = 1.5)

> axis(1, at = 1:10, labels = LETTERS[1:10])
> axis(2, las = 1)
> box()
```


Using Arrows as Error Bars
7.5
7.0
6.5
6.0
5.5
5.0
A
B
C
D
E
F
G
H
I
J

Drawing Rectangles

The basic call has the form:

```
rect(x0, y0, x1, y1, col=str, border=str)
```

where

- `x0`, `y0`, `x1`, `y1` give the coordinates of diagonally opposite corners of the rectangles.
- `col` and `border` specify the colour of the interior and border of the rectangles.
- line texture and width specifications can also be given.

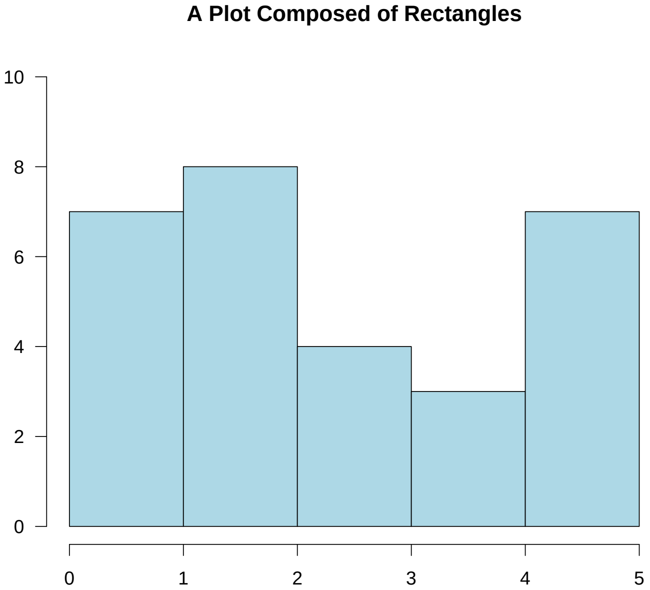
Rectangle Example

The following code illustrates how a barplot or histogram could be constructed.

```
> plot.new()
> plot.window(xlim = c(0, 5),
              ylim = c(0, 10))

> rect(0:4, 0, 1:5, c(7, 8, 4, 3),
       col = "lightblue")

> axis(1)
> axis(2, las = 1)
```


A Plot Composed of Rectangles
0
2
4
6
8
10
0
1
2
3
4
5

Drawing Polygons

The basic call has the form:

```
polygon(x, y, col=str, border=str)
```

where

- `x` and `y` give the coordinates of the polygon vertexes. `NA` values separate polygons.
- `col` and `border` specify the colour of the interior and border of the polygons.
- line texture and width specifications can also be given.

A Simple Polygon Example

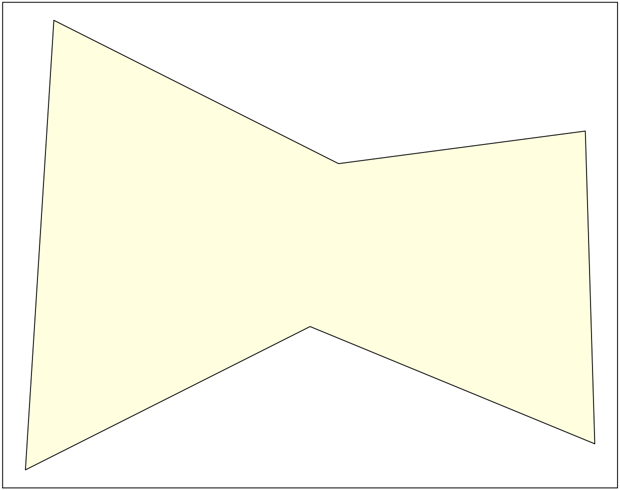
Here is a simple example which shows how to produce a simple polygon in a plot.

```
> x = c(0.32, 0.62, 0.88, 0.89, 0.59, 0.29)
> y = c(0.83, 0.61, 0.66, 0.18, 0.36, 0.14)
> plot.new()
> plot.window(xlim = range(x),
              ylim = range(y))

> polygon(x, y, col = "lightyellow")

> box()
```

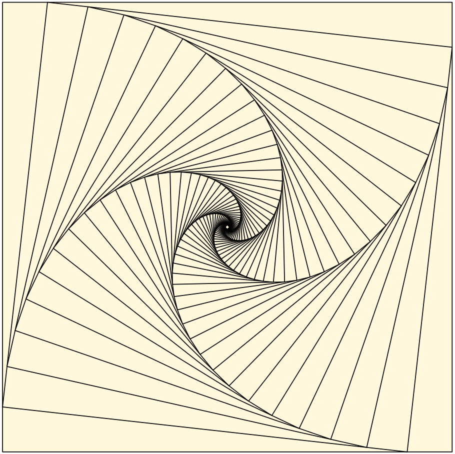
A Simple Polygon



Spiral Squares

```
> plot.new()
> plot.window(xlim = c(-1, 1),
              ylim = c(-1, 1), asp = 1)
> x = c(-1,  1,  1, -1)
> y = c( 1,  1, -1, -1)
> polygon(x, y, col = "cornsilk")
> vertex1 = c(1, 2, 3, 4)
> vertex2 = c(2, 3, 4, 1)
> for(i in 1:50) {
    x = 0.9 * x[vertex1] + 0.1 * x[vertex2]
    y = 0.9 * y[vertex1] + 0.1 * y[vertex2]
    polygon(x, y, col = "cornsilk")
  }
```

Spiral Squares



Drawing Text

The basic call has the form:

```
text(x, y, labels)
```

where

- `x` and `y` give the text coordinates.
- `labels` gives the actual text strings.

Optionally,

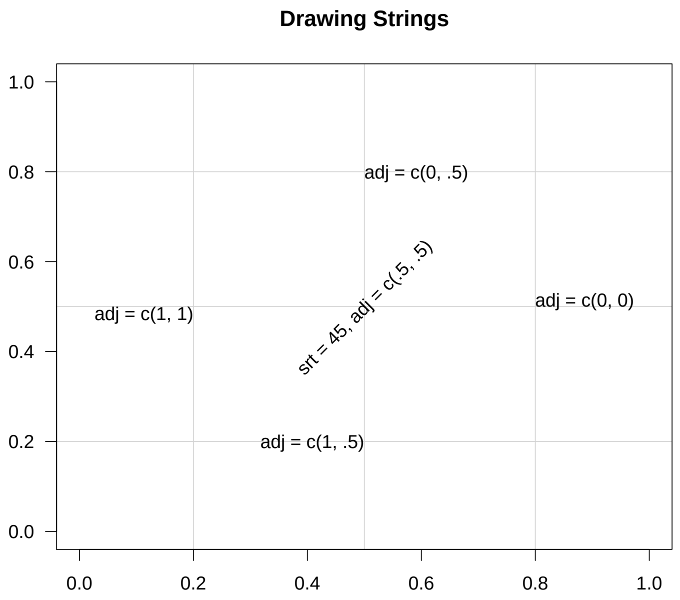
- `font` and `col` give the font and colour of the text,
- `srt` and `adj` give the rotation and justification of the strings.

A Text Example

```
> plot.new()
> plot.window(xlim = c(0, 1), ylim = c(0, 1))
> abline(h = c(.2, .5, .8),
         v = c(.5, .2, .8), col = "lightgrey")

> text(0.5, 0.5, "srt = 45, adj = c(.5, .5)",
       srt=45, adj=c(.5, .5))
> text(0.5, 0.8, "adj = c(0, .5)", adj = c(0, .5))
> text(0.5, 0.2, "adj = c(1, .5)", adj = c(1, .5))
> text(0.2, 0.5, "adj = c(1, 1)", adj = c(1, 1))
> text(0.8, 0.5, "adj = c(0, 0)", adj = c(0, 0))

> axis(1); axis(2, las = 1); box()
```


Drawing Strings
adj = c(0, .5)
srt = 45, adj = c(.5, .5)
adj = c(0, 0)
adj = c(1, 1)
adj = c(1, .5)
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0

Drawing a Legend

A simple example has the form:

```
legend(xloc, yloc, legend=text
       lty=linetypes, lwd=linewidths,
       pch=glyphname, col=colours,
       xjust=justification, yjust=justification)
```

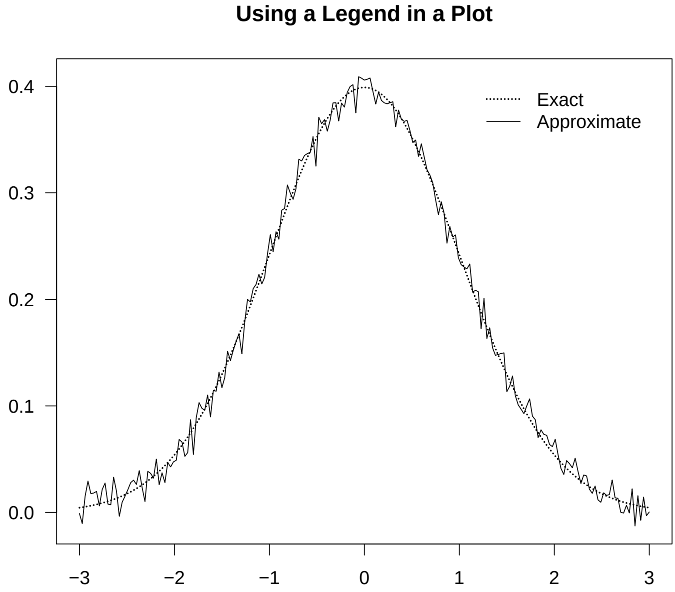
where

> `xloc` and `yloc` give the coordinates where the legend is to be placed and `xjust` and `yjust` give the justification of the legend box with respect to the location. The other values describe the legend contents.

The `legend` function is very flexible. Consult its manual entry for details.

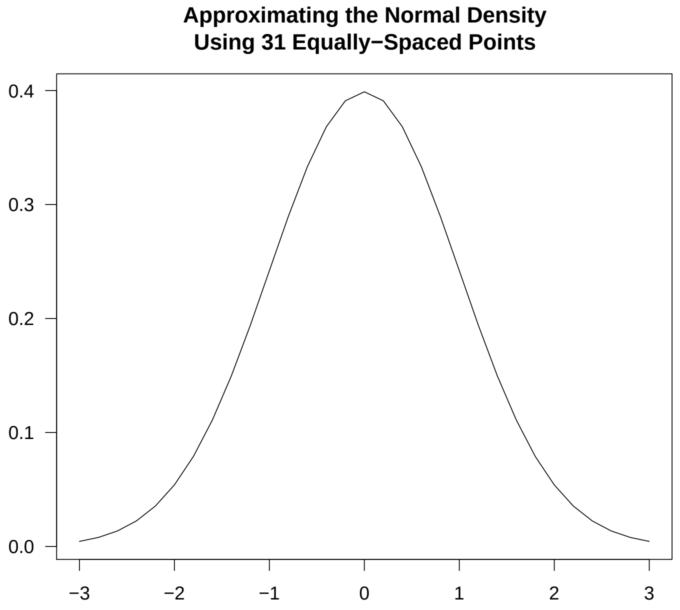
Legend

```
> xe = seq(-3, 3, length = 1001)
> ye = dnorm(xe)
> xa = seq(-3, 3, length = 201)
> ya = dnorm(xa) + rnorm(201, sd = .01)
> ylim = range(ye, ya)
> plot.new()
> plot.window(xlim = c(-3, 3), ylim = ylim)
> lines(xe, ye, lty = "11", lwd = 2)
> lines(xa, ya, lty = "solid", lwd = 1)
> legend(3, max(ylim),
         legend = c("Exact", "Approximate"),
         lty = c("11", "solid"),
         lwd = c(2, 1),
         xjust = 1, yjust = 1, bty = "n")
> axis(1); axis(2, las = 1); box()
```


Using a Legend in a Plot
Exact
Approximate
0.0
0.1
0.2
0.3
0.4
−3
−2
−1
0
1
2
3

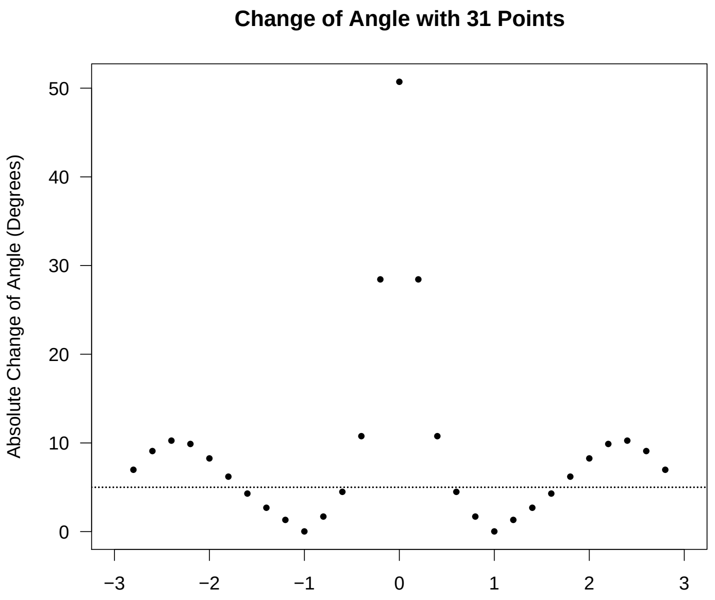
Drawing Curves

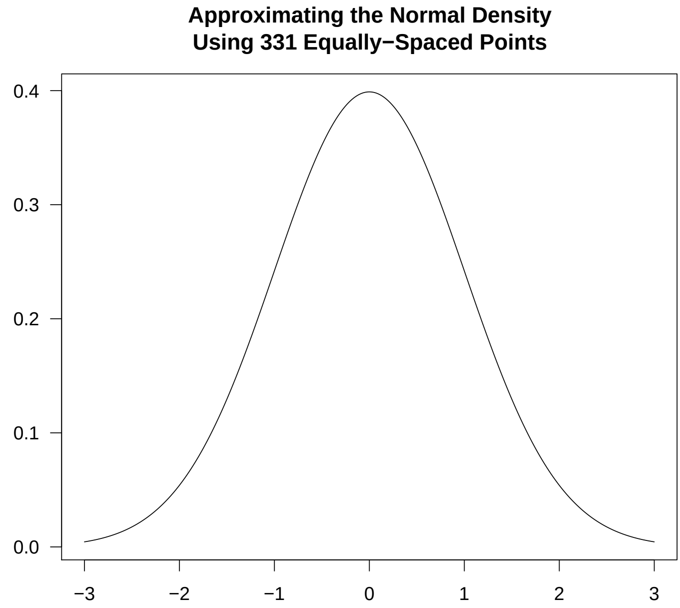
- There are no general curve drawing primitives available in R (yet).
- To draw a curve you must approximate it by a sequence of straight line segments.
- The question is how many line segments are required to obtain a visually "smooth" approximation to the curve.

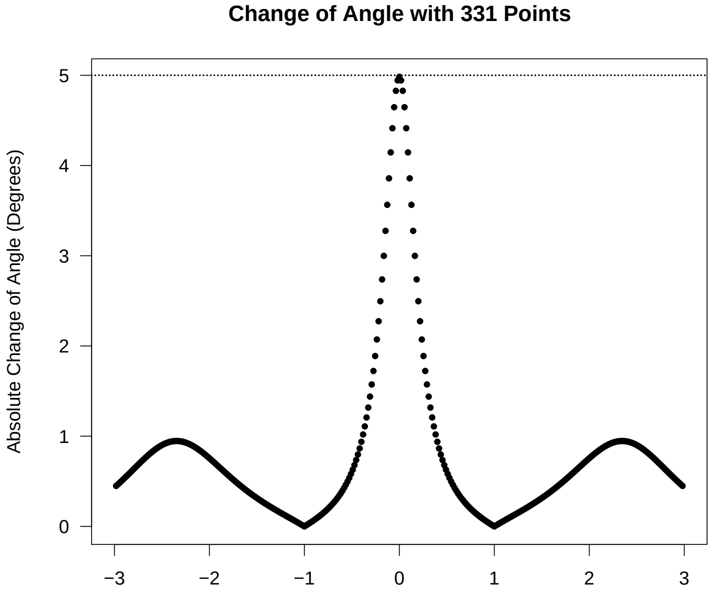

Approximating the Normal Density
Using 31 Equally−Spaced Points
0.4
0.3
0.2
0.1
0.0
−3
−2
−1
0
1
2
3

Lack of Smoothness

- Using 31 points to approximate the curve, there is a noticeable lack of smoothness in regions where the curve has high curvature.
- This is because our eye-brain system is good a detecting large changes of direction but sees changes in direction of less than $5°$ as "smooth."
- Checking the changes of angle in the approximation shows that there are some very large changes of angle.
- Increasing the number of approximating points to 331 means that there are no changes of direction which exceed $5°$.

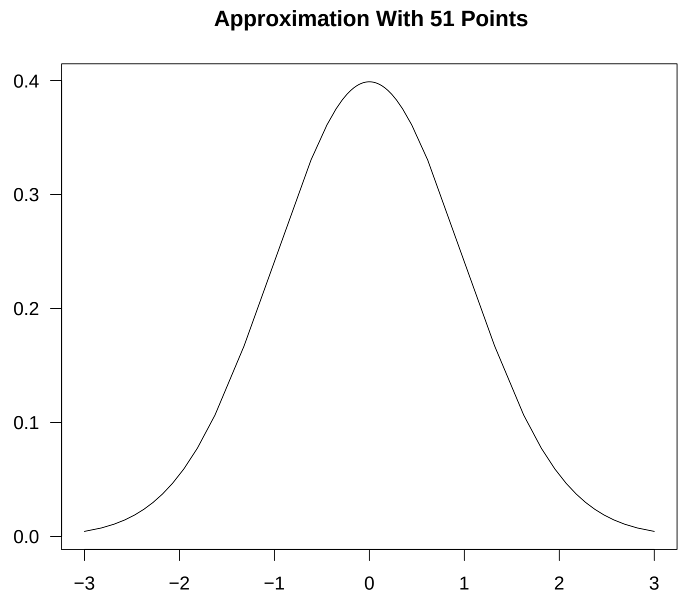

Change of Angle with 31 Points
Absolute Change of Angle (Degrees)
0
10
20
30
40
50
−3
−2
−1
0
1
2
3

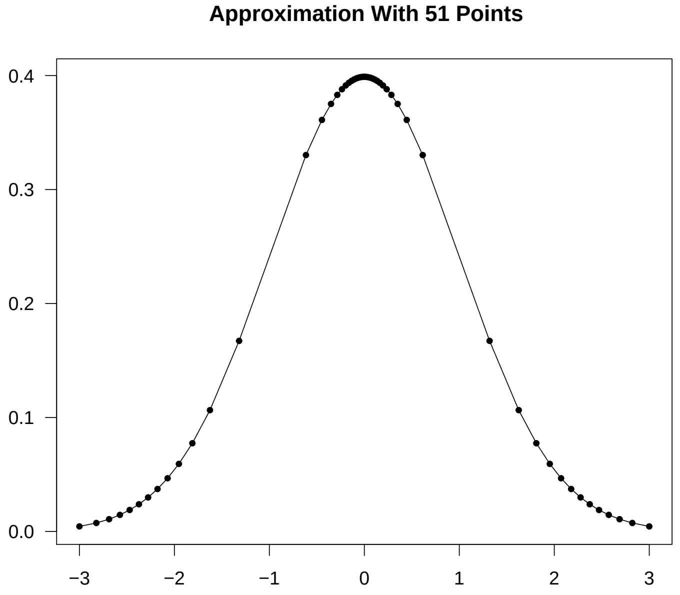

Approximating the Normal Density
Using 331 Equally−Spaced Points
0.4
0.3
0.2
0.1
0.0
−3
−2
−1
0
1
2
3


Change of Angle with 331 Points
Absolute Change of Angle (Degrees)
0
1
2
3
4
5
−3
−2
−1
0
1
2
3

Nonuniform Point Placement

- It is wasteful to use equally spaced points to approximate a curve. Regions with high curvature require closely packed points while regions of low curvature may need only a few points.
- This means that techniques which take account of curvature can lead to approximations with many fewer points.
- One technique is to place points so that the segment to segment direction change is less than a fixed threshold (e.g. $5°$).


Approximation With 51 Points
0.0
0.1
0.2
0.3
0.4
−3
−2
−1
0
1
2
3


Approximation With 51 Points
0.0
0.1
0.2
0.3
0.4
−3
−2
−1
0
1
2
3

Circles

The circle with centre (x_c, y_c) and radius R is defined by the equation

$$(x - x_c)^2 + (y - y_c)^2 = R^2.$$

It can also be defined parametrically with the equations

$$\begin{aligned} x(t) &= R\cos t \\ y(t) &= R\sin t \end{aligned}$$

for $t \in [0, 2\pi)$.

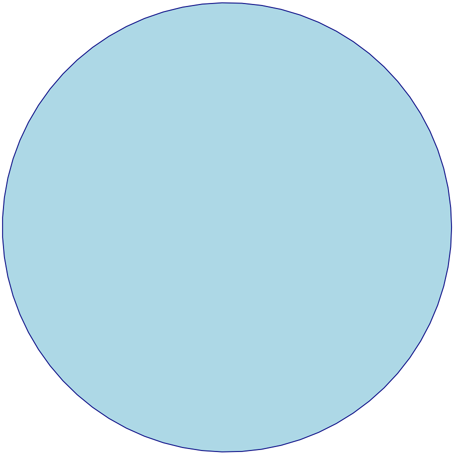
There is no simple R function for drawing a circle. Circles must be approximated with a regular polygon.

Using at least 71 vertexes for the polygon ensures that the change of direction between edges is less than or equal to 5°.

Drawing Circles

```
> R = 1
> xc = 0
> yc = 0
> n = 72
> t = seq(0, 2 * pi, length = n)[1:(n-1)]
> x = xc + R * cos(t)
> y = yc + R * sin(t)
> plot.new()
> plot.window(xlim = range(x),
              ylim = range(y), asp = 1)
> polygon(x, y, col = "lightblue",
          border = "navyblue")
```

A 71−Vertex Polygon Approximating a Circle



Ellipses

An ellipse is a generalisation of circle defined by the equation:

$$\left(\frac{x - x_c}{a}\right)^2 + \left(\frac{y - y_c}{b}\right)^2 = 1.$$

An ellipse can be defined in parametric form by:

$$x(t) = a\cos t + x_c,$$
$$y(t) = b\sin t + y_c,$$

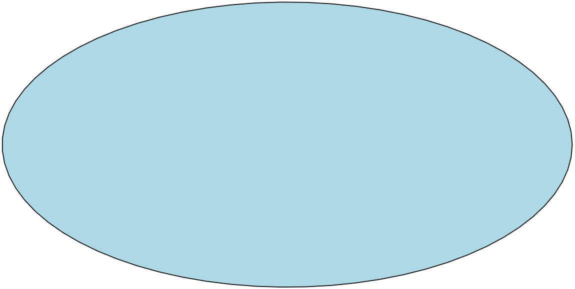
with $t \in [0, 2\pi)$.

The distortion of the ellipse happens in such a way that it can be approximated by the same number of straight line segments as a circle.

Drawing Ellipses

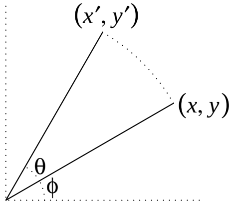
```
> a = 4
> b = 2
> xc = 0
> yc = 0
> n = 72
> t = seq(0, 2 * pi, length = n)[1:(n-1)]
> x = xc + a * cos(t)
> y = yc + b * sin(t)
> plot.new()
> plot.window(xlim = range(x),
              ylim = range(y),
              asp = 1)
> polygon(x, y, col = "lightblue")
```

An Ellipse



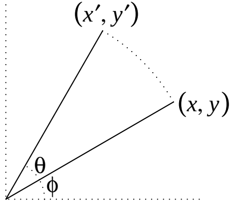
Rotation

We want to rotate (x, y) through an angle θ about the origin to (x', y').



Rotation

We want to rotate (x, y) through an angle θ about the origin to (x', y').

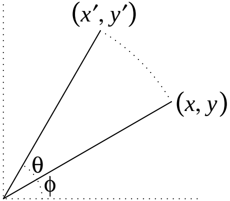


In polar coordinates:

$$x = R\cos\phi,$$
$$y = R\sin\phi.$$

Rotation

We want to rotate (x, y) through an angle θ about the origin to (x', y').



In polar coordinates:

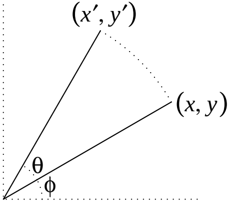
$$x = R\cos\phi,$$
$$y = R\sin\phi.$$

and:

$$x' = R\cos(\phi + \theta) \qquad y' = R\sin(\phi + \theta)$$

Rotation

We want to rotate (x, y) through an angle θ about the origin to (x', y').



In polar coordinates:

$$x = R\cos\phi,$$
$$y = R\sin\phi.$$

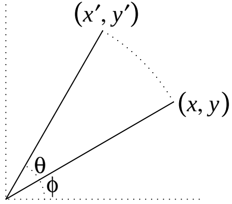
and:

$$x' = R\cos(\phi + \theta) \\ = R(\cos\phi\cos\theta - \sin\phi\sin\theta)$$

$$y' = R\sin(\phi + \theta) \\ = R(\cos\phi\sin\theta + \sin\phi\cos\theta)$$

Rotation

We want to rotate (x, y) through an angle θ about the origin to (x', y').



In polar coordinates:

$$
\begin{aligned}
x &= R\cos\phi, \\
y &= R\sin\phi.
\end{aligned}
$$

and:

$$
\begin{aligned}
x' &= R\cos(\phi+\theta) \\
&= R(\cos\phi\cos\theta - \sin\phi\sin\theta) \\
&= x\cos\theta - y\sin\theta
\end{aligned}
\qquad
\begin{aligned}
y' &= R\sin(\phi+\theta) \\
&= R(\cos\phi\sin\theta + \sin\phi\cos\theta) \\
&= x\sin\theta + y\cos\theta
\end{aligned}
$$

Rotation Formulae

If the point (x, y) is rotated though an angle θ around the origin to a new position (x', y') then

$$
\begin{aligned}
x' &= x\cos\theta - y\sin\theta \\
y' &= x\sin\theta + y\cos\theta,
\end{aligned}
$$

or in matrix terms

$$
\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}.
$$

Rotated Ellipses

Often it is useful to consider rotated ellipses rather than ellipses aligned with the coordinate axes. This can be done by simply applying a rotation.

If the ellipse is rotated by an angle θ, its equation is

$$\begin{aligned} x(t) &= a\cos t\cos\theta - b\sin t\sin\theta + x_c \\ y(t) &= a\cos t\sin\theta + b\cos t\sin\theta + y_c \end{aligned}$$

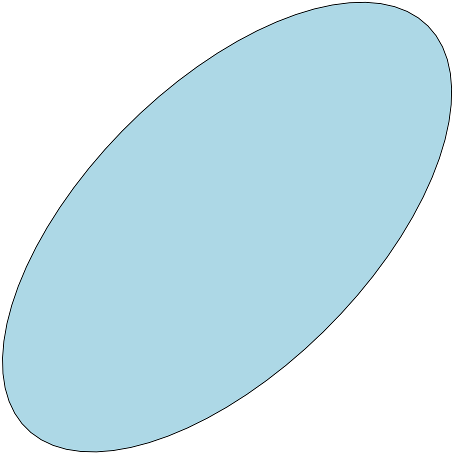
for $t \in [0, 2\pi)$.

Again, the same number of straight line segments can be used to approximate the ellipse.

Drawing Rotated Ellipses

```
> a = 4
> b = 2
> xc = 0
> yc = 0
> n = 72
> theta = 45 * (pi / 180)
> t = seq(0, 2 * pi, length = n)[1:(n-1)]
> x = xc + a * cos(t) * cos(theta) -
          b * sin(t) * sin(theta)
> y = yc + a * cos(t) * sin(theta) +
          b * sin(t) * cos(theta)
> plot.new()
> plot.window(xlim = range(x),
              ylim = range(y), asp = 1)
> polygon(x, y, col = "lightblue")
```

A Rotated Ellipse



Ellipses in Statistics

Suppose that (X_1, X_2) has a bivariate normal distribution, with X_i having mean μ_i and variance σ_i^2, and the correlation between X_1 and X_2 being ρ.

If we define

$$d = \arccos \rho,$$

the equations

$$\begin{aligned} x &= \mu_1 + k\,\sigma_1 \cos(t + d), \\ y &= \mu_2 + k\,\sigma_2 \cos(t), \end{aligned}$$

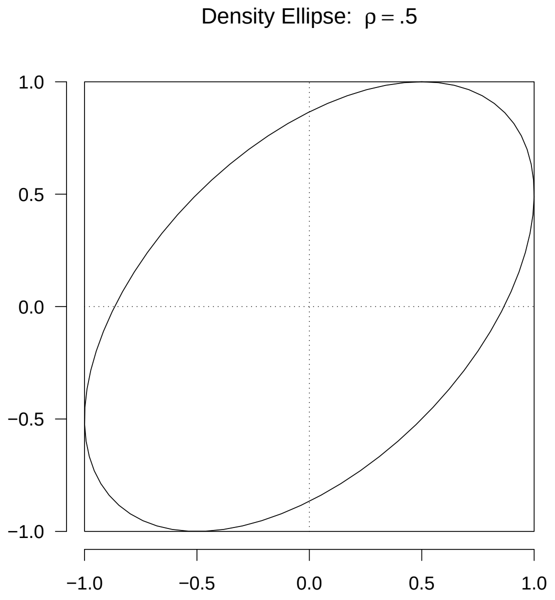
describe the contours of the density of (X_1, X_2).

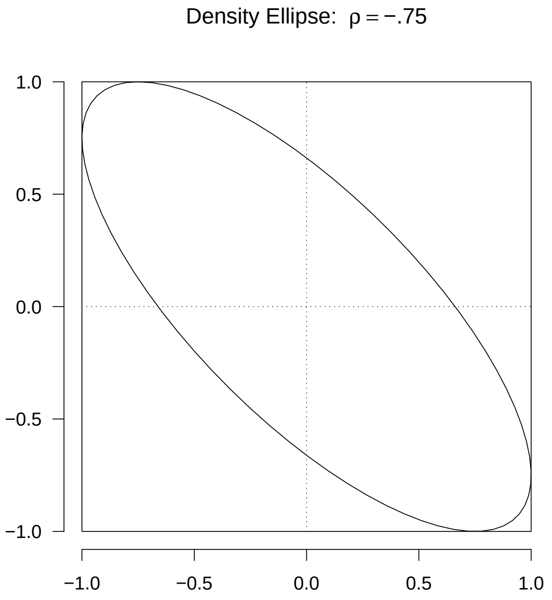
Choosing the appropriate value for k makes it possible to draw prediction ellipses for the bivariate normal distribution.

Statistical Ellipses

Here $\mu_1 = \mu_2 = 0$, $\sigma_1 = \sigma_2 = 1$ and $k = 1$.

```
> n = 72
> rho = 0.5
> d = acos(rho)
> t = seq(0, 2 * pi, length = n)[1:(n-1)]
> plot.new()
> plot.window(xlim = c(-1, 1),
              ylim = c(-1, 1), asp = 1)
> rect(-1, -1, 1, 1)
> polygon(cos(t + d), y = cos(t))
> segments(-1, 0, 1, 0, lty = "13")
> segments(0, -1, 0, 1, lty = "13")
> axis(1); axis(2, las = 1)
```


Density Ellipse: ρ = .5
1.0
0.5
0.0
−0.5
−1.0
−1.0
−0.5
0.0
0.5
1.0



Density Ellipse: ρ = −.75
1.0
0.5
0.0
−0.5
−1.0
−1.0
−0.5
0.0
0.5
1.0

Spirals

A spiral is a path which circles a point at a radial distance which is changing monotonically.

$$x(t) = R(t)\cos t$$
$$y(t) = R(t)\sin t$$

for $t > 0$.

In particular, an *exponential spiral* is obtained when

$$R(t) = \alpha^t$$

where $\alpha < 1$.

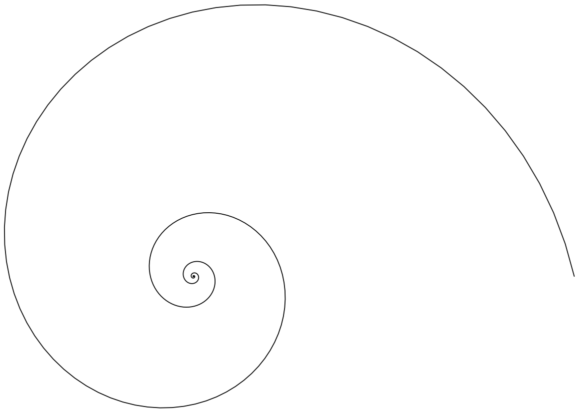
Such a path resembles a snail or nautilus shell.

Drawing a Spiral

These commands draw a spiral, centred on $(0, 0)$. The spiral does 5 revolutions:

```
> k = 5
> n = k * 72
> theta = seq(0, k * 2 * pi, length = n)
> R = .98^(1:n - 1)
> x = R * cos(theta)
> y = R * sin(theta)
> plot.new()
> plot.window(xlim = range(x),
              ylim = range(y), asp = 1)
> lines(x, y)
```

An Exponential Spiral



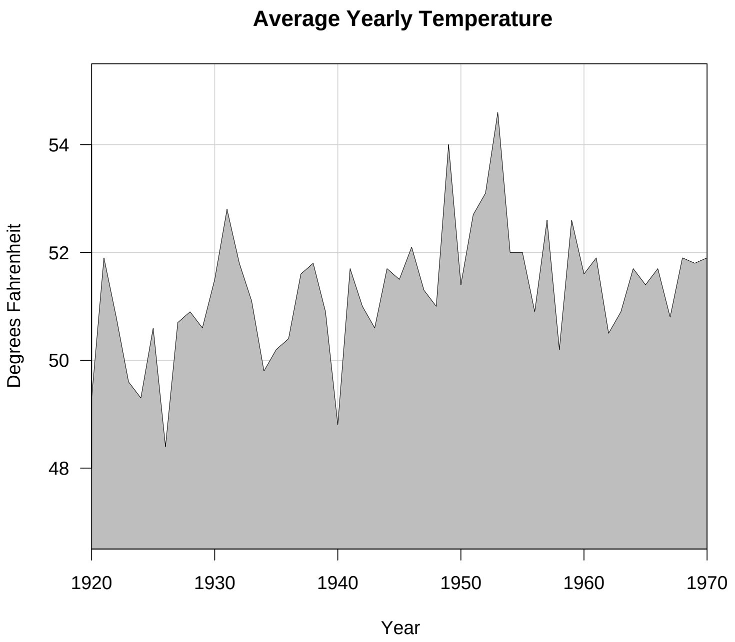
Filling Areas In Line Graphs

Annual year temperatures in New Haven (1920-1970).

```
> y
 [1] 49.3 51.9 50.8 49.6 49.3 50.6 48.4
 [8] 50.7 50.9 50.6 51.5 52.8 51.8 51.1
[15] 49.8 50.2 50.4 51.6 51.8 50.9 48.8
[22] 51.7 51.0 50.6 51.7 51.5 52.1 51.3
[29] 51.0 54.0 51.4 52.7 53.1 54.6 52.0
[36] 52.0 50.9 52.6 50.2 52.6 51.6 51.9
[43] 50.5 50.9 51.7 51.4 51.7 50.8 51.9
[50] 51.8 51.9
```

The corresponding years.

```
> x = 1920:1970
```


Average Yearly Temperature
Degrees Fahrenheit
54
52
50
48
1920
1930
1940
1950
1960
1970
Year

Plot Construction

Setting up the plot and drawing the background grid.

```
plot.new()
plot.window(xlim = c(1920, 1970), xaxs = "i",
            ylim = c(46.5, 55.5), yaxs = "i")

abline(v = seq(1930, 1960, by = 10),
       col = "grey")
abline(h = seq(48, 54, by = 2), col = "grey")
```

Drawing the filled polygon.

```
xx = c(1920, x, 1970)
yy = c(46.5, y, 46.5)
polygon(xx, yy, col = "grey")
```

Finishing up

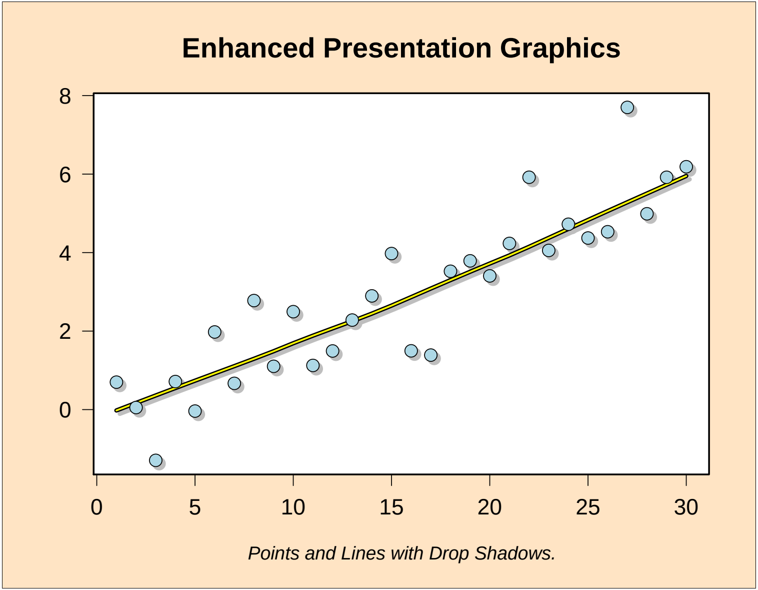
Add the axes, bounding box and annotation.

```
axis(1)
axis(2, las = 1)
box()
title(main = "Average Yearly Temperature")
title(ylab = "Degrees Fahrenheit")
title(xlab = "Year")
```

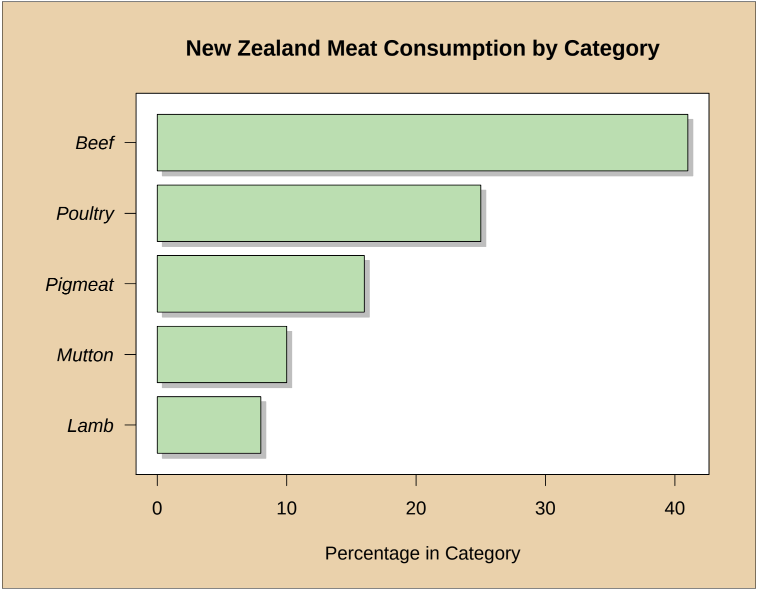
Some Graphics Examples

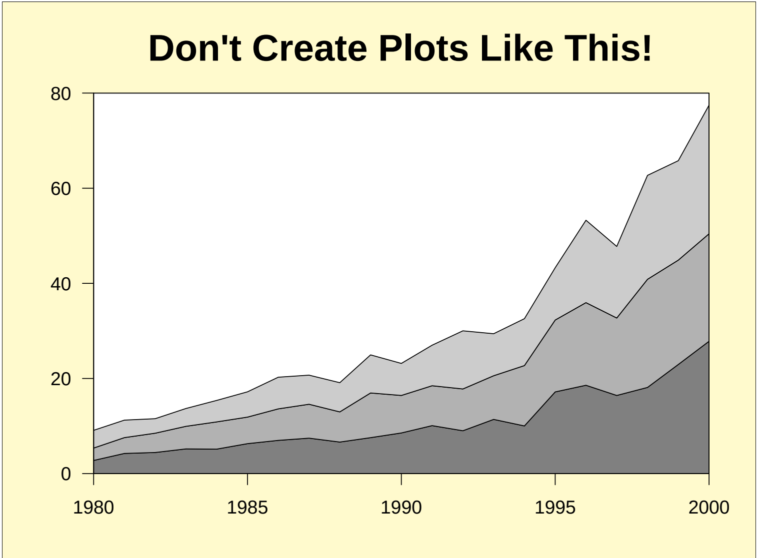
Here is a short set of examples to show the kind of graphics that is possible to create using the R graphics primitives.

These are not necessarily all “good” graphs. They just show what is possible with a little effort.

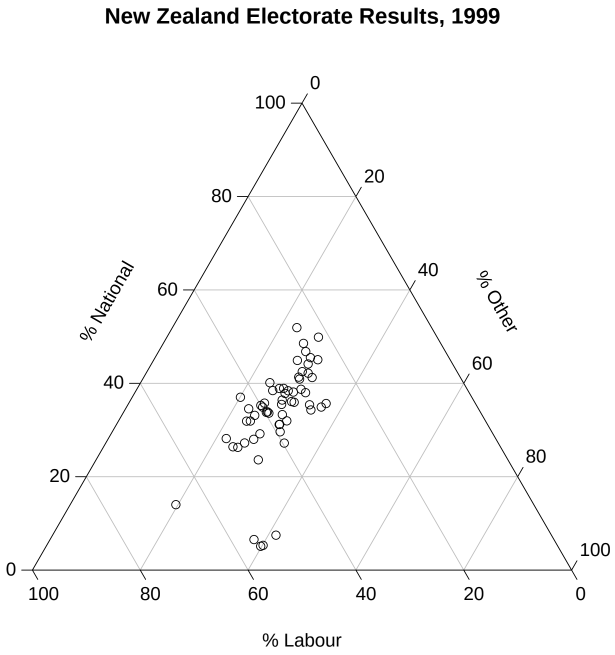


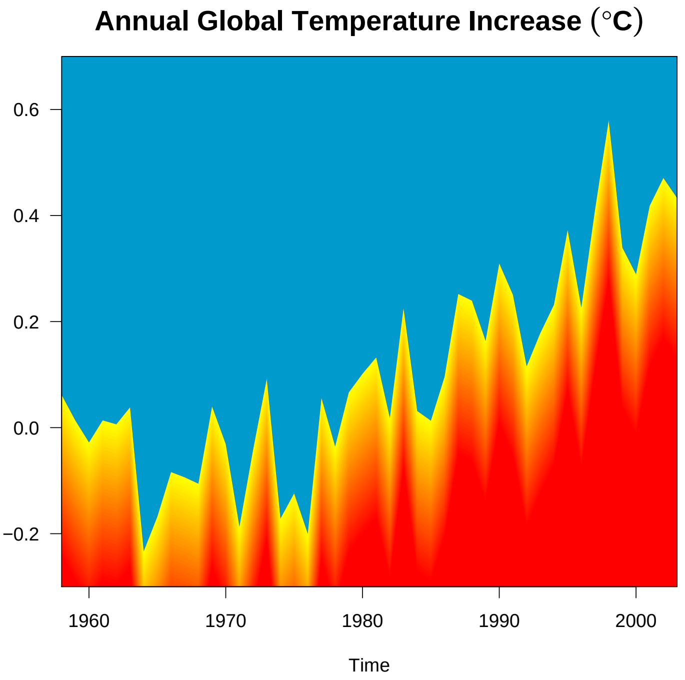
Enhanced Presentation Graphics
8
6
4
2
0
0
5
10
15
20
25
30
Points and Lines with Drop Shadows.


New Zealand Meat Consumption by Category
Beef
Poultry
Pigmeat
Mutton
Lamb
0
10
20
30
40
Percentage in Category



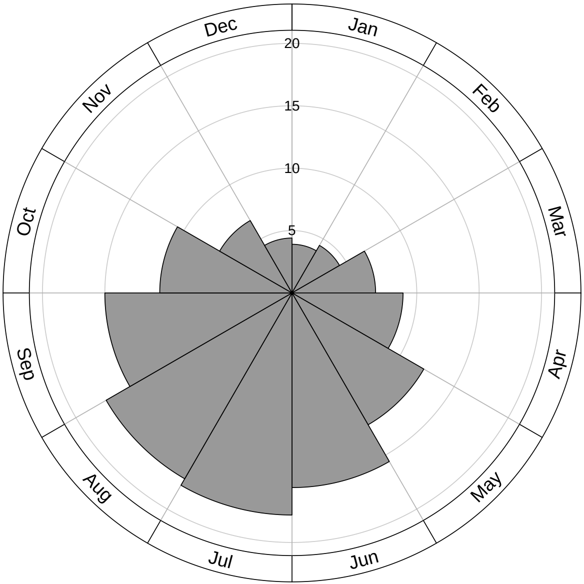
Not even in the privacy of your own room.


New Zealand Electorate Results, 1999
0
100
20
80
40
60
60
40
80
20
100
0
100
80
60
40
20
0
% National
% Other
% Labour

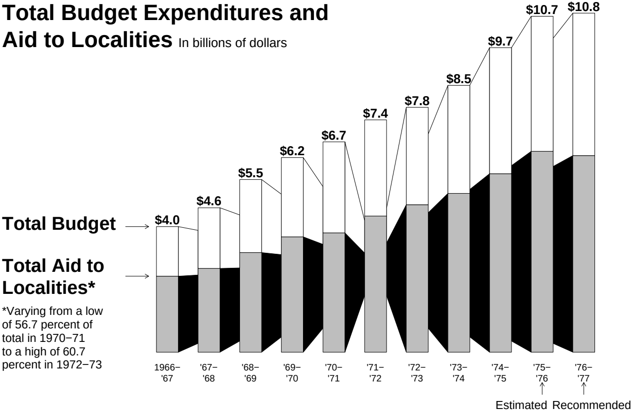


Annual Global Temperature Increase (°C)
0.6
0.4
0.2
0.0
−0.2
1960
1970
1980
1990
2000
Time

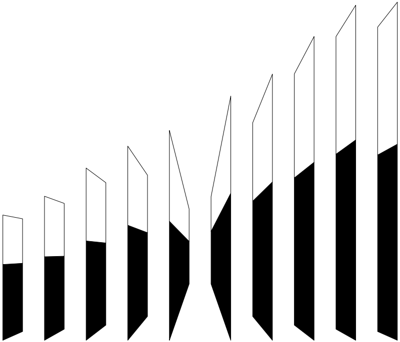
Average Monthly Temperatures in London

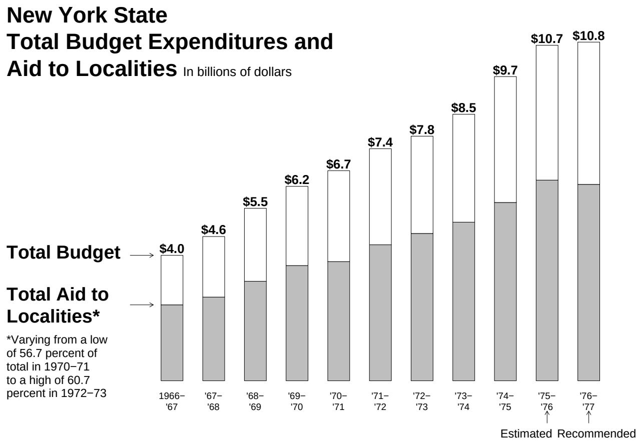


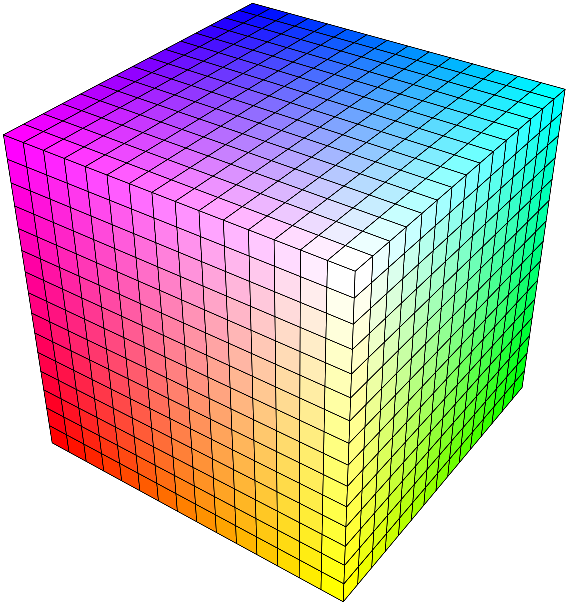
New York State Total Budget Expenditures and Aid to Localities In billions of dollars

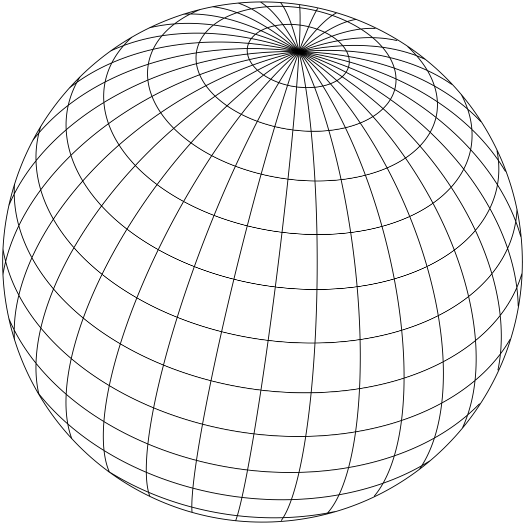


*Varying from a low of 56.7 percent of total in 1970–71 to a high of 60.7 percent in 1972–73

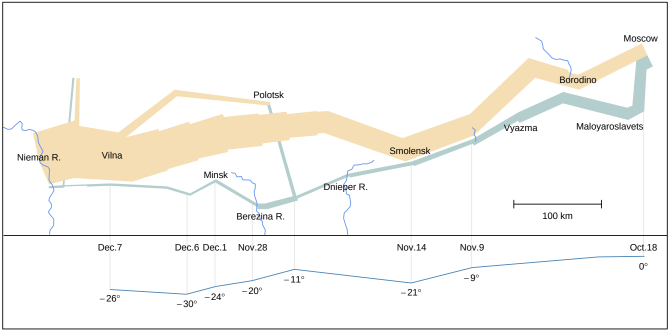



New York State
Total Budget Expenditures and
Aid to Localities In billions of dollars
Total Budget
Total Aid to Localities*
*Varying from a low of 56.7 percent of total in 1970–71 to a high of 60.7 percent in 1972–73
$4.0
$4.6
$5.5
$6.2
$6.7
$7.4
$7.8
$8.5
$9.7
$10.7
$10.8
1966–'67
'67–'68
'68–'69
'69–'70
'70–'71
'71–'72
'72–'73
'73–'74
'74–'75
'75–'76
'76–'77
Estimated
Recommended





The Minard Map of Napoleon's 1812 Campaign in Russia



Packaging Graphics Functionality

We have seen lots of ways of drawing graphs. Now let's look at how this capability can be packaged as general purpose tools (i.e. R functions).

There are two types of tool to consider.

- Tools which set up and draw a complete plot,
- Tools which add to existing plots.

The tools are slightly simplified versions of real tools which are part of R, or can be found in extension libraries.

A Scatterplot Function

There are a number of tasks which must be solved:

- Determining the x and y ranges.
- Setting up the plot window.
- Plotting the points.
- Adding the plot axes and frame.

Each of these tasks is relatively simple.

Scatterplot Code

Here are the key steps required to produce a scatterplot.

- Determine the x and y ranges.

```
xlim = range(x)
ylim = range(y)
```

- Set up the plot window.

```
plot.new()
plot.window(xlim = xlim, ylim = ylim)
```

- Plot the points.

```
points(x, y)
```

A Scatterplot Function

By “wrapping” the steps in a function definition we can produce a simple scatter plot function.

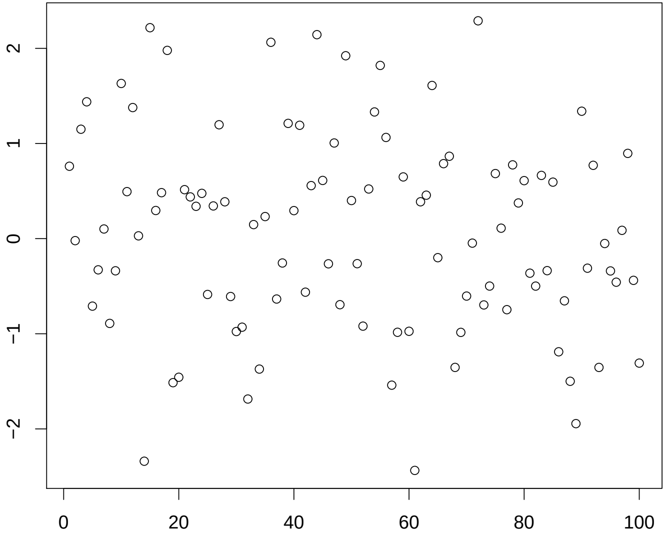
```
> scat =
      function(x, y) {
        xlim = range(x)
        ylim = range(y)
        plot.new()
        plot.window(xlim = xlim, ylim = ylim)
        points(x, y)
        axis(1)
        axis(2)
        box()
  }
```

Using The Scatterplot Function

We can use this function just like any other R function to produce scatter plots.

```
> xv = 1:100
> yv = rnorm(100)
> scat(xv, yv)
> title(main = "My Very Own Scatterplot")
```

My Very Own Scatterplot



Customisation

The `scat` function is very restricted in what it can do. Let's add a little flexibility.

- Optional plotting symbol specification
- Optional colour specification
- Optional range specification
- Optional logarithmic axes
- Optional annotation

The Customised Scatterplot Function

```
> scat =
    function(x, y, pch = 1, col = "black",
             log = "", asp = NA,
             xlim = range(x, na.rm = TRUE),
             xlim = range(y, na.rm = TRUE),
             main = NULL, sub = NULL,
             xlab = NULL, ylab = NULL) {
      plot.new()
      plot.window(xlim = xlim, ylim = ylim,
                  log = log, asp = asp)
      points(x, y, pch = pch, col = col)
      axis(1); axis(2); box()
      title(main = main, sub = sub,
            xlab = xlab, ylab = ylab)
  }
```

An Ellipse Drawing Function

Now we show a function which can be draw a single ellipse with centre (`ax`,`yc`), axis lengths `a` and `b` and rotated by `theta` degrees.

It is possible to pass the function parameters which change the colour of the ellipse and its border, and to change the line type used for the border.

A real ellipse drawing function would be more complex (but harder to fit onto a single slide).

An Ellipse Drawing Function

```
> ellipse =
    function(a = 1, b = 1, theta = 0,
             xc = 0, yc = 0, n = 72, ...)
    {
        t = seq(0, 2 * pi, length = n)[-n]
        theta = theta * (pi / 180)
        x = xc + a * cos(theta) * cos(t) -
            b * sin(theta) * sin(t)
        y = yc + a * sin(theta) * cos(t) +
            b * cos(theta) * sin(t)
        polygon(x, y, ...)
  }
```

Querying and Specifying Graphics State

The `par` function provides a way of maintaining graphics state in the form of a variety of *graphics parameters*.

The call

```
> par(mar = c(4, 4, 2, 2))
```

sets the plot margins to consist of 4, 4, 2 and 2 lines of text.

The call

```
> par("mar")
```

returns the current setting of the `mar` parameter.

There are a *large* number of graphics parameters which can be set and retrieved with `par`.

Device, Figure and Plot Size Enquiries

The graphics system uses inches as its basic measure of length. Note that 1 inch = 2.54 cm.

`par("din")` :	the device dimensions in inches,
`par("fin")` :	the current figure dimensions in inches,
`par("pin")` :	the current plot region dimensions in inches,
`par("fig")` :	NDC coordinates for the figure region,
`par("plt")` :	NDC coordinates for the plot region,

NDC = normalised device coordinates.

User Coordinate System Enquiries

The upper and lower x and y limits for the plot region may not be exactly those specified by a user (because of a possible 6% expansion). The exact limits can be obtained as follows:

```
> usr = par("usr")
```

After this call, `usr` will contain a vector of four numbers. The first two are the left and right x scale limits and the second two are the bottom and top y scale limits.

A call to `par` can also be used to change the limits.

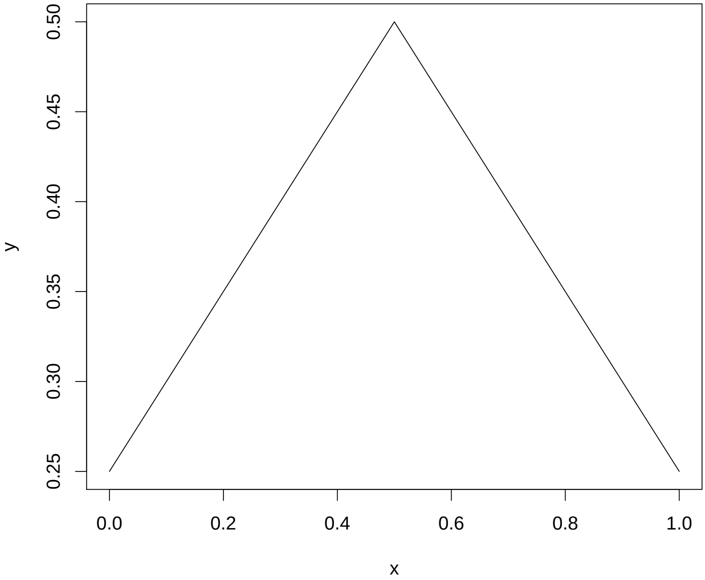
```
> par(usr = c(0, 1, 10, 20))
```

The specified limits must be sensible.

Computing Direction Change in Degrees

Here is a sketch of how the change of angle computations were done in the "smooth curve" examples. This works by transforming from data units to inches.

```
> x = c(0, 0.5, 1.0)
> y = c(0.25, 0.5, 0.25)
> plot(x, y, type = "l")
> dx = diff(x)
> dy = diff(y)
> pin = par("pin")
> usr = par("usr")
> ax = pin[1]/diff(usr[1:2])
> ay = pin[2]/diff(usr[3:4])
> diff(180 * atan2(ay * dy, ax * dx) / pi)
[1] -115.2753
```



0.50
0.45
0.40
0.35
0.30
0.25
y
0.0
0.2
0.4
0.6
0.8
1.0
x

Multifigure Layouts

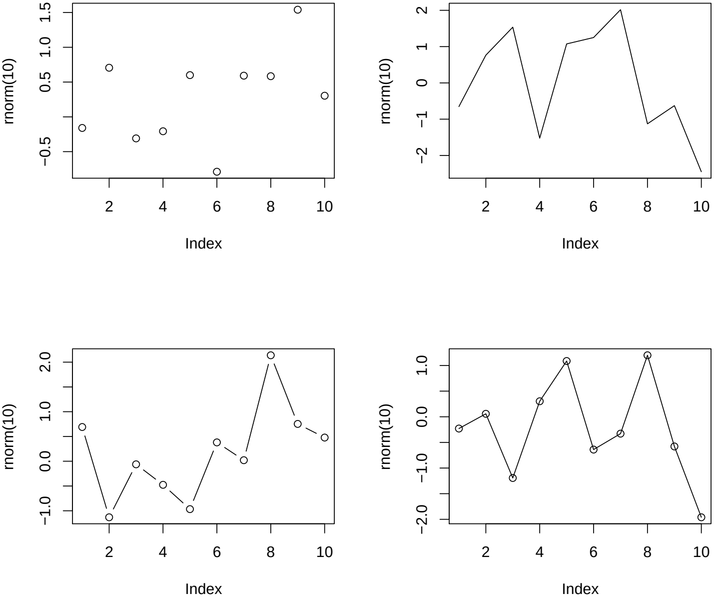
`par` can be used to set up arrays of figures on the page. These arrays are then filled row-by-row or column-by-column.

The following example declares a two-by-two array to be filled by rows and then produces the plots.

```
> par(mfrow=c(2, 2))
> plot(rnorm(10), type = "p")
> plot(rnorm(10), type = "l")
> plot(rnorm(10), type = "b")
> plot(rnorm(10), type = "o")
```

A two-by-two array to be filled by columns would be declared with

```
> par(mfcol = c(2, 2))
```



rnorm(10)
Index
1.5
1.0
0.5
−0.5
2
4
6
8
10
rnorm(10)
Index
2
1
0
−1
−2
rnorm(10)
Index
2.0
1.0
0.0
−1.0
rnorm(10)
Index
1.0
0.0
−1.0
−2.0

Eliminating Waste Margin Space

It can be useful to eliminate redundant space from multi-way arrays by trimming the margins a little.

```
> par(mfrow=c(2, 2))
> par(mar = c(5.1, 4.1, 0.1, 2.1))
> par(oma = c(0, 0, 4, 0))
> plot(rnorm(10), type = "p")
> plot(rnorm(10), type = "l")
> plot(rnorm(10), type = "b")
> plot(rnorm(10), type = "o")
> title(main = "Plots with Margins Trimmed",
        outer = TRUE)
```

Here we have trimmed space from the top of each plot, and placed a 4 line *outer margin* at the top of of the layout.

Plots with Margins Trimmed